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COMPUTATIONAL FLUID DYNAMICS FOR MISSILES

by

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COMPUTATIONAL FLUID DYNAMICS FOR MISSILES

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SUMMARY

A brief non-mathematical introduction to the subject of Computational Fluid Dynamics, (CFD), is given. Various approximations to the full flow equations are described and their suitability for modelling the aerodynamics of missiles is discussed. A number of CFD codes available in the UK which are applicable to missile aerodynamics are considered. Each code is described briefly and comparisons between prediction and measurement are shown.

Paper presented at the RAeS One-Day Conference on Weapon Aerodynamics, 1 December 1988.

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1 INTRODUCTION

Traditionally, the aerodynamic loads on a missile shape have been obtained from wind-tunnel tests and semi-empirical methods. The costs associated with wind-tunnel testing have remained approximately level in real terms over the last few years, whereas the cost of computing has been reducing as faster machines with larger memories have become available. There could, therefore, be considerable benefit from reducing the amount of wind-tunnel testing and increasing the calculation of missile aerodynamic loads using computers.

Semi-empirical prediction methods have been used for many years and they have the advantage of not requiring large computer resources. These methods depend on experimental data-bases as input to a simple theoretical framework. The more comprehensive the experimental data, the wider the ranges of missile configurations and flight envelopes that can be handled with confidence. However, because of the practical difficulties of providing an experimental data-base covering all possible missile configurations, all semi-empirical methods are restricted to a range of configurations. For example, in general they are limited to missile shapes with circular cross-section bodies. For several reasons, including packaging and low radar cross-section, missiles with non-circular cross-section bodies have been considered in the last few years.

The combination of falling computing costs and the inability of semi-empirical methods to handle some of the new configurations led to Computational Fluid Dynamics (CFD) being applied to missile shapes. For conventional shapes, CFD methods are more expensive to run than semi-empirical methods but they can provide more accurate predictions and can supply information such as surface pressures and shock wave positions.

This paper gives a brief non-mathematical introduction to CFD and describes a number of CFD codes which are applicable to missile configurations.

2 INTRODUCTION TO CFD

2.1 What is CFD?

CFD can be summarised as the numerical solution of a set of partial differential equations which describe the motion of a fluid. For the aerodynamicist, the fluid of interest is normally air. The equations model the laws of conservation of mass, momentum, and energy, and link pressure, density, and velocity components. They are non-linear and cannot usually be solved analytically. Even numerically there are difficulties and approximate forms of the full equations are usually solved. For instance, the viscosity is often neglected.

The numerical solution is found at a finite number of discrete points in the flowfield, which are normally arranged to form a structured grid. The missile or aircraft configuration affects the solution through the mathematical boundary conditions. For instance, at points on a solid body, no flow is allowed normal to the surface. The calculated pressures at all such points can be integrated to provide aerodynamic loads.

2.2 The Navier-Stokes equations and their approximations

The equations which contain a full description of the flow of a perfect gas are known as the Navier-Stokes equations. The solution of these equations would require calculations involving minute length and time scales in order to resolve turbulence. This would imply a very large number of grid points in the flowfield and present day computers are not large or fast enough to cope with such calculations, even for a simple missile shape.

Most attempts to solve the Navier-Stokes equations numerically involve a turbulence model which enables the use or larger length and time scales. The equations are then known as the Reynolds-averaged Navier-Stokes equations. A large number of grid points are still required in order to resolve the viscous features such as the boundary layer.

If it is assumed that the viscous terms are negligible except those associated with velocity gradients normal to a solid surface, the Thin-Layer Navier-Stokes equations are obtained. The solution of this set of equations requires grid points with fine spacing in the directions normal to the surface but wider spacing is adequate in the streamwise (and spanwise) directions.

The Parabolised Navier-Stokes equations are applicable to supersonic flows and they assume that the subsonic part of the boundary layer is small and that the time dependent terms can be neglected. The solution takes advantage of the supersonic nature of the flow and uses a space-marching technique (see section 2.6). In this way the computing requirements are considerably reduced.

If all the viscous terms are removed from the Navier-Stokes equations, the Euler equations are obtained. Most of the current CFD methods for missiles solve the Euler equations.

Further approximations can be made. The assumption of a flow potential gives rise to the Full Potential equation but implies a lack of vorticity in the calculations. The further assumption that deviations from the free stream conditions are small leads to the Transonic Small Perturbation (TSP) equation.

2.3 CFD applied to missiles

Methods for solving the TSP and Full Potential equations have been applied successfully to transonic wing design, but they have only limited application to missiles. These methods cannot deal with strong shocks and cannot model vorticity in the flow. These restrictions lead to severe Mach number and angle of attack limitations for the missile aerodynamicist. Methods which solve the Euler equations are applicable over larger ranges of Mach number and angle of attack.

Navier-Stokes methods provide a better model of the physics of the flow because they include viscosity. However, they require considerably more computing resources than Euler methods and the results are sensitive to the turbulence model used. At present in the UK, the missile aerodynamicist usually only uses Navier-Stokes methods where the flow is dominated by viscous effects (*eg* base flows).

2.4 Separation Modelling

A common feature of flows past missiles at moderate to high angle of attack is the body vortex, which arises as a result of flow separation from the body. Normally, the inviscid Euler equations would not model this important feature because flow separation is a viscous phenomenon. However, it is desirable to model the vortex and the Euler equations do support vorticity. The ability to model the body vortex is prevented only by the lack of flow separation. There has been considerable effort on the application of forced flow separation at empirically defined separation lines. The validity of this approach is dubious from the mathematical point of view, but some of the results are encouraging.

2.5 Grids

It is convenient to consider the points at which we obtain solutions to the flow equations as the nodes of a net or grid covering the flowfield. It is straightforward to construct a reasonable grid around a simple shape such as an axisymmetric body. More difficult is the construction of a grid around a complete finned missile. There are several options and Fig 1 shows some examples of grids in two dimensions.

In the wraparound grid, one set of grid lines follows the configuration surface, while the other set is approximately normal to the surface. It is desirable to have grid points closely spaced where large gradients in flow variables are expected, but the wraparound grid is generally difficult to construct even without such considerations.

In a multiblock (three dimensional) or multizone (two dimensional) approach the flowfield is split into a number of blocks or zones, each of which can be gridded in a straightforward manner.

A non-aligned grid is simply a Cartesian grid superimposed on the configuration. This grid is easy to set up but the application of the boundary conditions when the equations are solved can be difficult.

Unstructured grids are very flexible but keeping track of neighbouring points can be difficult, and also it is not easy to take advantage of vector processing.

Most CFD codes for missiles use grids produced by the multiblock or multizone approach.

2.6 Time-marching and space-marching

Time-marching and space-marching are two approaches to solving the flow equations, and both have been used in CFD methods for missiles. In the time-marching technique, the equations retain their time dependent terms even through a steady state solution is sought. A three dimensional grid is constructed for the whole flowfield and a guess is made for the initial state of the flow variables at all the points of the grid. A suitable guess may be 'free stream conditions everywhere'. The solution is then stepped forward in time until convergence (or steady state) is obtained. Time-marching can be thought of as an iterative process, and is valid over the whole Mach number range.

In space-marching methods, the time-dependent terms in the equations are ignored. Space-marching methods are applicable only to flows which are entirely supersonic, and advantage is taken of the lack of upstream influence in such flows. Given a starting solution in an upstream plane, or slice of the flowfield, the flow in a plane or slice a short distance downstream can be calculated. This procedure is repeated until the whole flowfield is known. In this approach, a two dimensional grid is produced at each step and the computing requirements are considerably less than those for the time-marching approach.

3 CFD FOR MISSILES IN THE UK

3.1 Summary of methods

In this country the application of CFD to missiles in isolation is almost entirely based upon Euler methods, which can conveniently be separated into space-marching and time-marching codes. On the space-marching side, RAE has been fortunate to obtain SWINT, MUSE, and ZEUS, codes developed in the USA at the Naval Surface Warfare Center. There are two time-marching Euler methods of interest to

missile aerodynamicists at RAE, the Weapons Multiblock Suite, (WMS), developed by BAe Dynamics Division, and a code developed by the University of Salford.

There are also some Navier-Stokes methods. BAFL2 is a RARDE code applicable to base flow and exhaust plume calculations, and a Thin Layer Navier-Stokes Code (TLNS) for artillery shells is under development at RARDE.

This paper will concentrate on the methods applicable to finned configurations or bodies at high angles of attack. Further discussion is thus limited to the Euler methods.

3.2 SWINT

SWINT[1] stands for Supersonic Wing INlet Tail, describing some of the geometrical features it can handle. It is a space-marching method which solves the Euler equations for the inviscid supersonic flow between a missile and its bow shock, given initial data in a crossflow plane near the nose (Fig 2). It can handle a body, which need not be axisymmetric, and wings and fins which are assumed to be thin. Some intakes can also be considered.

In practice SWINT does not work well at the lower supersonic speeds and Mach 2 is effectively the lower limit. The angle of attack limit is highly Mach number and configuration dependent. Results have been obtained at an angle of attack as high as 27.5 degrees (for one configuration and one Mach number), but generally the angle of attack limit is somewhat lower. The reasons for the Mach number and angle of attack boundaries will be discussed in section 4.

Several modifications have been made to SWINT in the UK. Firstly, a parametric geometry input scheme has been introduced which simplifies the definition of the configuration geometry. Secondly, the original SWINT code would allow the modelling of flow separation from the body only for symmetric flow cases (*eg* a missile with cruciform fins at 0 or 45 degrees roll). RAE has extended the separation modelling to configurations at arbitrary roll orientation. Finally, CPU times on the Cray 1S computer have been cut by one third so that a typical calculation now takes about one minute of CPU time.

Fig 3 shows a comparison between prediction and measurement of normal force coefficient for a missile with a cruciform fin arrangement tested at Mach 3.5. The agreement is excellent up to 24 degrees angle of attack.

Fig 4 shows the corresponding comparison of centre of pressure position in calibres. Again the predictions are excellent, being within 0.2 of a calibre of the measurements over the whole angle of attack range. This agreement is considerably better than would be expected from a semi-empirical method. Normal force

predictions of good semi-empirical methods are generally within 10% of measured values and centre of pressure agreement is typically within 0.5 of a calibre.

It should be noted that the SWINT predictions have been produced using the option of flow separation from the body. This enables the body vortices and their interaction with downstream lifting surfaces to be modelled. This interaction is particularly important when fin loads are being considered. Fig 5 shows a comparison of predicted and measured loads on a deflected fin as the whole configuration is rolled through 360 degrees. When the fin is near the most leeward position there is an interaction with the body vortices as shown by the 'S-bend' in the results in that region. This feature has been predicted well by the UK version of SWINT. The only poor agreement is near the 270 degree position, where the local angle of attack is a maximum and difficulties might be expected.

Further comparisons between SWINT predictions and experimental measurements may be found in Ref 2.

3.3 MUSE

The MUSE code (MUltizone Supersonic Euler)[3] is a development of SWINT. Assessment has shown that MUSE is less robust than SWINT and it is difficult to use. The multizone grid allows MUSE to handle configurations which SWINT cannot, but it is considered that the use of such configurations at Mach numbers above 2 will be rare. RAE has decided not to implement the MUSE code.

3.4 ZEUS

ZEUS (Zonal EUler Solver)[4] is a more recent space-marching Euler code from NSWC which differs from SWINT in the way the Euler equations are discretised and solved. It uses a multizone grid which avoids the thin fin approximation used in SWINT but it cannot handle as wide a range of configurations as MUSE.

Assessment by BAe Dynamics Division, Filton, under contract from RAE, has shown that ZEUS is a robust code which is easier to use than SWINT. Its accuracy is similar to that of SWINT, but computer times are approximately doubled.

During the assessment, a parametric geometry input scheme was incorporated, which simplifies the definition of the configuration geometry. It is intended to add a model of flow separation from the body, and with this modification, ZEUS will almost certainly replace SWINT as the standard space-marching code for missiles at RAE.

As an example of ZEUS results, Fig 6 shows comparisons between measured and calculated pressures on the surface of an elliptic cross-section body at Mach 2.5[5].

The configuration is rolled 45 degrees and results are shown for angles of attack of 5, 10 and 15 degrees. The station chosen is towards the rear of the configuration, and the breaks in the prediction curves correspond to fin positions. Despite the complex shape, the ZEUS predictions are in close agreement with the measured pressures.

3.5 Weapons Multiblock Suite (WMS)

WMS[6] was developed by BAe Dynamics Division at Filton under an MoD contract funded by RAE. It is appropriate for transonic flows and the multiblock grid generator allows WMS to be applied to complex geometries.

Fig 7 shows a three dimensional block structure around a typical missile shape. This is a symmetric case and half the flowfield has been divided into sixteen blocks. Each block has a three dimensional grid constructed within it before the calculation of the flow starts.

Fig 8 shows the boundary of the grid on the surface of a configuration. The high density of grid points on the fins was produced in order to model more accurately the flow in that region.

Fig 9 shows a comparison of measured and predicted surface pressures for the configuration shown in Fig 8 at 2 degrees angle of attack to a Mach 1.05 free stream. The pressures shown are along the length of the body at an angle of 55 degrees from the most leeward position. Agreement is excellent over the nose section. Over the parallel section of the body, the agreement is reasonable, but on the afterbody the predictions are poor. The viscous effects associated with the junction of the body and the sting would be having a strong influence on the afterbody pressures, and it is the lack of viscosity in the Euler code which is causing the poor agreement in the region.

3.6 Salford code

The other time-marching Euler code of interest to RAE was developed at the University of Salford[7]. It is suitable for transonic and supersonic flows but is limited to body alone configurations. The code is not available outside Salford but it is mentioned here because it is being used to explore the possibilities of flow separation modelling. This work is being funded by RAE. The problem of modelling flow separation from a smooth surface in an Euler code can be divided into two parts, the location of the separation position, and the technique of forcing flow separation there. The work at Salford has concentrated on the latter and has resulted in some success. It is intended to incorporate the Salford separation model into the WMS code.

Fig 10 shows a comparison between predicted and measured pressure distributions at one station on a missile-type body at an angle of 16 degrees to the Mach 2.5 free stream. Two predicted pressure distributions are shown, corresponding to calculations with and without the flow separation modelling. Both calculations show good agreement with measurement on the windward side of the body. On the leeward side, the calculation without separation modelling shows the pressure continuing to fall beyond the experimentally observed flow separation position, and the calculated flow recompresses through a strong crossflow shock. The calculation with flow separation forced at the experimentally observed position provides much better agreement with measurement on the leeward side of the body.

Having modelled the flow separation with some success, work is now in progress on the prediction of its location.

4 PRESENT CAPABILITY

Fig 11 shows our present Mach number and angle of attack capability with CFD methods. Two boundary curves are shown, one for the space-marching method, SWINT, and the other for the time-marching Weapons Multiblock Suite. Each curve shows the maximum angle of attack for which it has been possible to obtain a complete calculation, for a range of Mach numbers. It should be emphasised that the SWINT boundary is highly configuration dependent, and the curve shown is based on a typical finned configuration. Some of the features of this curve will appear in the boundaries for other configurations.

Being a space-marching method, SWINT relies on the flow being supersonic everywhere. If a subsonic patch is discovered the calculation stops. The part of the SWINT boundary between Mach 2 and Mach 3.5 (in this case) corresponds to the occurrence of a subsonic patch. As expected, the higher the free stream Mach number, the higher the angle of attack at which a subsonic patch appears.

SWINT calculates the flow between a missile and its bow shock and the whole configuration must be contained within the bow shock. The part of the SWINT boundary above Mach 3.5 corresponds to the bow shock impinging on one of the fins of the configuration. As expected, increasing the Mach number lowers the angle of attack limit because the bow shock is closer to the body.

The boundary for WMS is not so dependent on the configuration. For Mach numbers up to about 2, the angle of attack is limited by the lack of a flow separation model. It is hoped that this part of the boundary will be raised considerably when the Salford separation model has been implemented in WMS.

At higher Mach numbers the numerical scheme for solving the Euler equations is unsuitable, being designed for transonic flows.

5 CONCLUSIONS

(1) Methods based on the Euler equations are currently the most popular CFD codes for missile applications.

(2) Navier-Stokes methods are necessary for flows dominated by viscous effects (*eg* base flows).

(3) Separation modelling in an Euler method can increase its angle of attack range and improve predictions.

(4) In general, CFD methods are applicable to a wider range of configurations and can produce more accurate results than semi-empirical methods, although considerably more computer resources are required.

(5) Work on several CFD methods for missiles is in progress or planned in order to improve the UK's capability in this area.

LIST OF SYMBOLS

C_n	Normal Force coefficient
C_{np2}	Panel Normal Force coefficient for fin 2 (always normal to panel surface)
C_p	Pressure coefficient
D	Body diameter
L	Body Length
M	Mach number
X	Axial distance forward from nose
$\overline{X}$	-X
X_{cp}	Centre of Pressure position (axial)
ζ	Rudder deflection angle
λ	Roll angle of configuration
σ	Angle of attack
ϕ	Circumferential angle

REFERENCES

No.	Author	Title, etc
1	A.B. Wardlaw F.P. Baltakis J.M. Solomon	An inviscid computational method for tactical missile configurations. NSWC TR 81-457 (1981)
2	J. Hodges L.C. Ward	The RAE experimental data-base for missiles at high Mach number and its use in assessing CFD methods. Paper 32, AGARD CP428, Aerodynamics of Hypersonic Lifting Vehicles, (1987)
3	A.B. Wardlaw F.J. Priolo J.M. Solomon	A multiple zone method for supersonic tactical missiles. NSWC TR 85-484 (1986)
4	A.B. Wardlaw S.F. Davis	A second order Godunov method for supersonic tactical missiles. NSWC TR 86-506 (1986)
5	F.J. Priolo A.B. Wardlaw	Supersonic non-circular missile computations. AIAA 88-0278 (1988)
6	P.A. Shepherd G.R. Tod	Development and application of a Weapons Multiblock Suite. AGARD CP437, Vol 1, Validation of Computational Fluid Dynamics, (1988)
7	D.M. Causon P.J. Ford	Improvements in techniques for the numerical simulation of steady transonic flows. AIAA 84-0089 (1984)

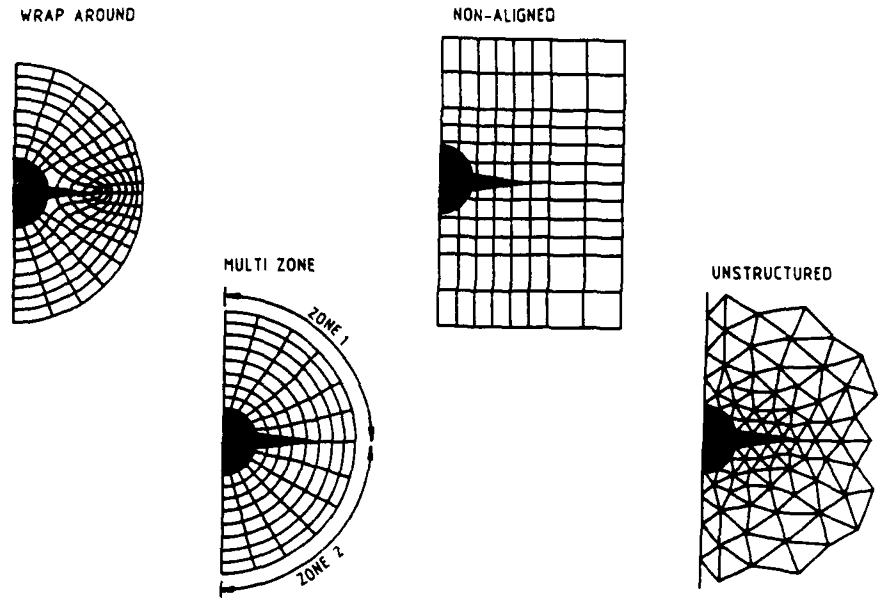

Fig 1 Grid types

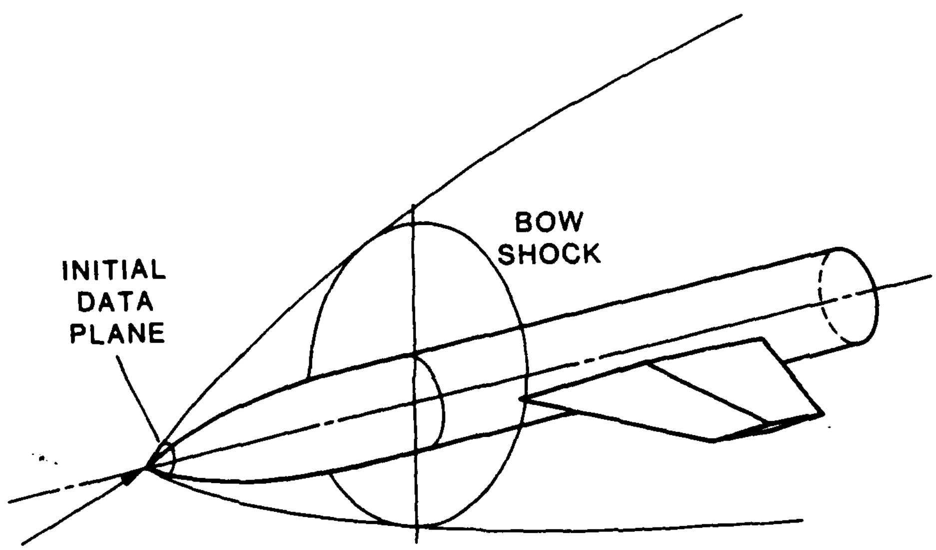

Fig 2 Initial data plane and bow shock, defining region of computed flow for SWINT

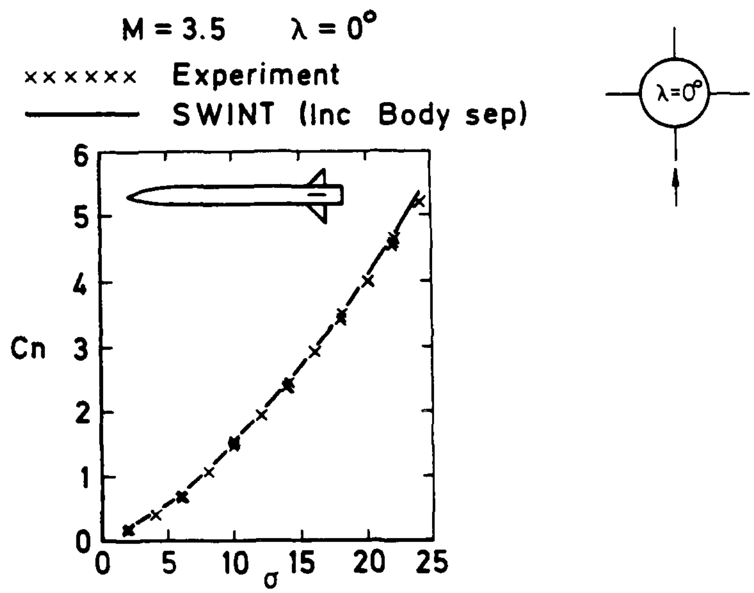

Fig 3 Overall normal force, SWINT prediction and experiment

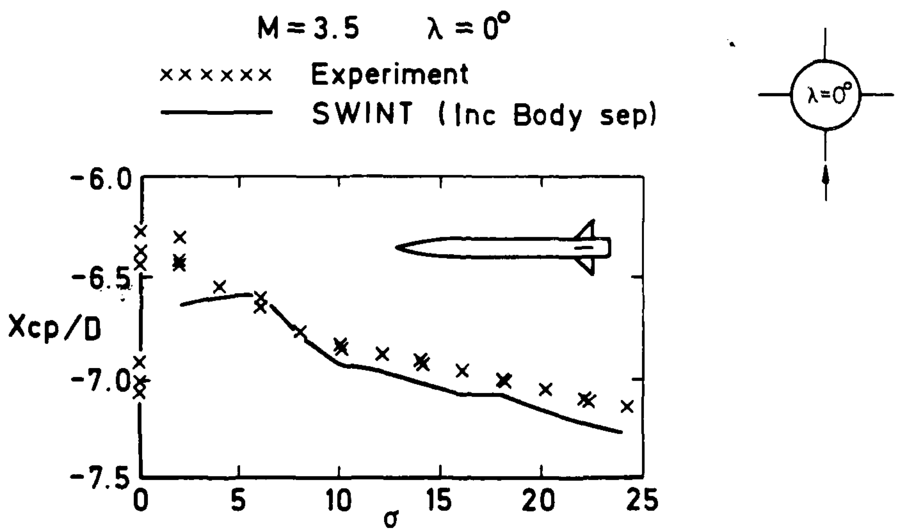

Fig 4 Centre of pressure, SWINT prediction and experiment

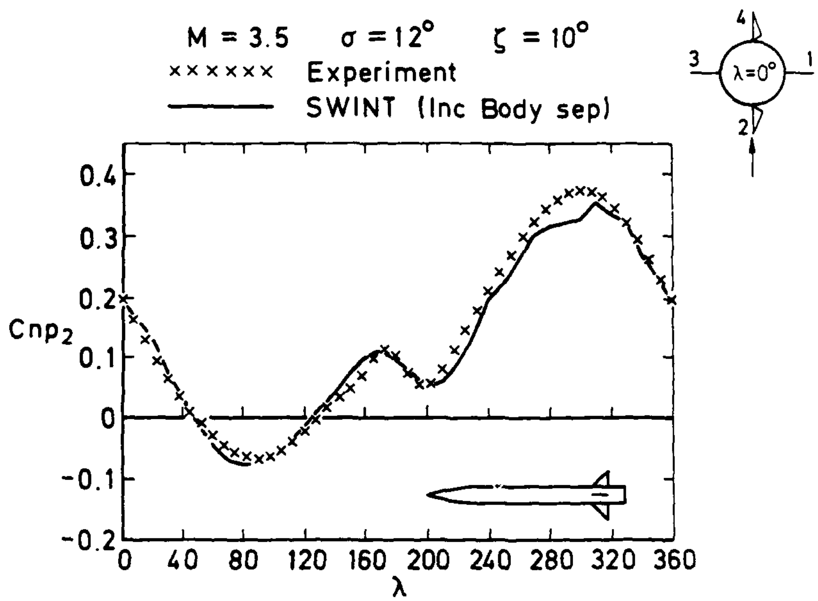

Fig 5 Normal force on deflected fin, SWINT prediction and experiment

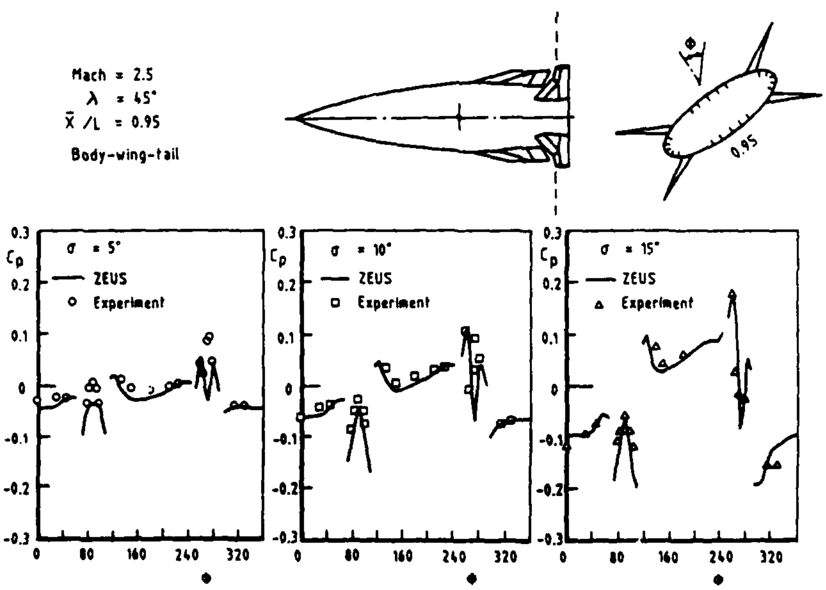

Fig 6 Body surface pressures, ZEUS prediction and experiment (Ref 5)

Figs 7, 8&9

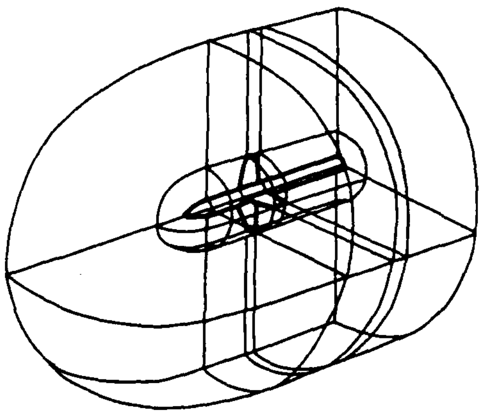

Fig 7 WMS block structure

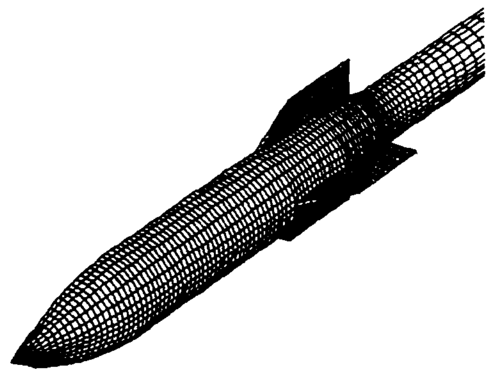

Fig 8 WMS surface grid

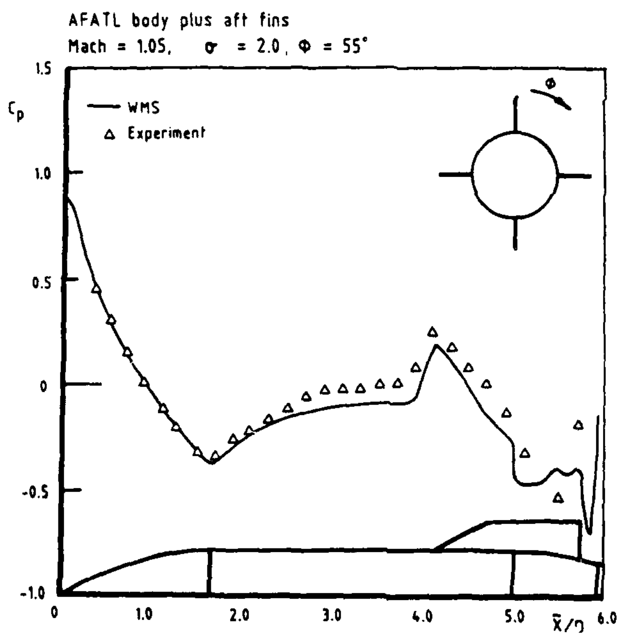

Fig 9 Body surface pressures, WMS prediction and experiment

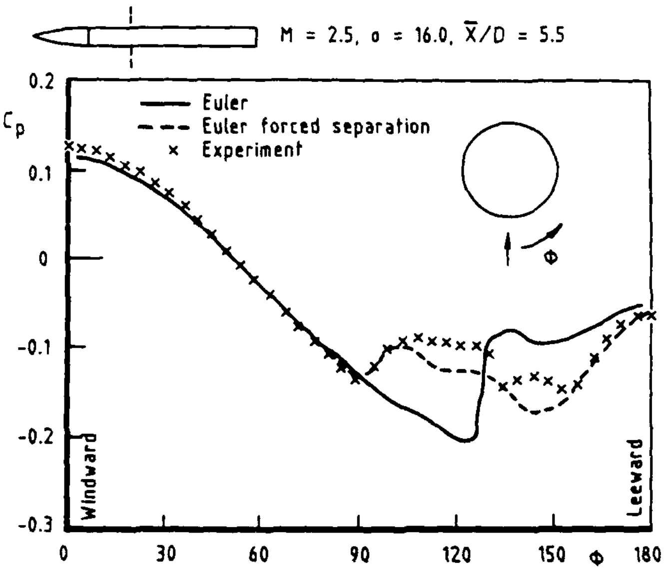

Fig 10 Body surface pressures, Salford predictions and experiment

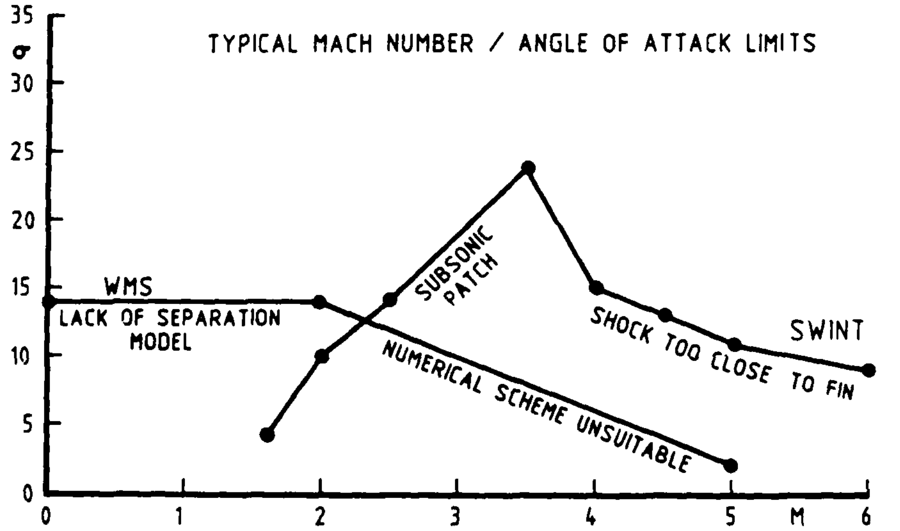

Fig 11 Mach number and angle of attack capability

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

CFD. Missiles.

17. Abstract

A brief non-mathematical introduction to the subject of Computational Fluid Dynamics, (CFD), is given. Various approximations to the full flow equations are described and their suitability for modelling the aerodynamics of missiles is discussed. A number of CFD codes available in the UK which are applicable to missile aerodynamics are considered. Each code is described briefly and comparisons between prediction and measurement are shown.

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